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Title: Microseismic monitoring of CO2-injection-induced seismicity

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Microseismic monitoring of CO₂-injection-induced seismicity

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Objectives

Microseismic monitoring of CO₂-injection-induced seismicity:

- Studying moment tensors of microseismic sources
- Imaging fracture zones and subsurface structure
- Obtaining three-dimension seismic velocity model and improved moment tensors





Outline

- Introduction
- Adaptive moment-tensor joint inversion
- Reverse-time migration
- Full-waveform inversion
- Conclusions





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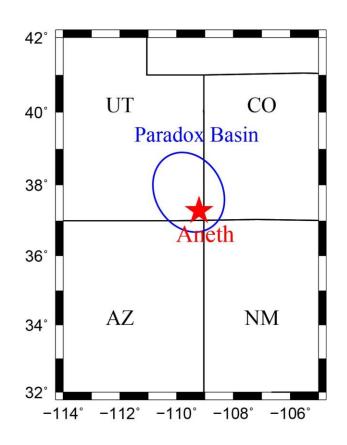
- Carbon Capture, Utilization and Storage (CCUS) for reducing the greenhouse gas emission
- CO₂ injection for Enhance Oil Recovery (EOR)
- Monitoring CO₂ reservoir for long-term storage
- Microseismic monitoring: low cost and high efficient



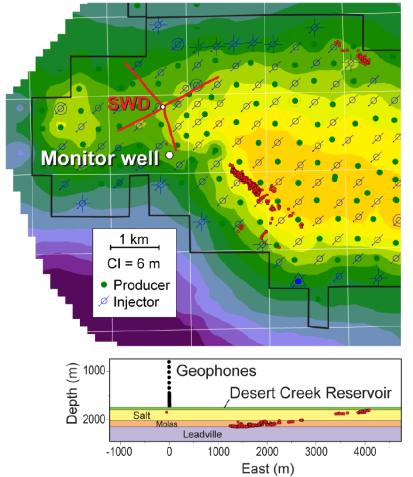


The Aneth CO₂-enhanced oil recovery (EOR) field at Utah

- CO₂ injection from 2007 to 2009
- 23 geophones within a vertical well spanning from 800 to 1700 m



(Soma and Rutledge, 2013)

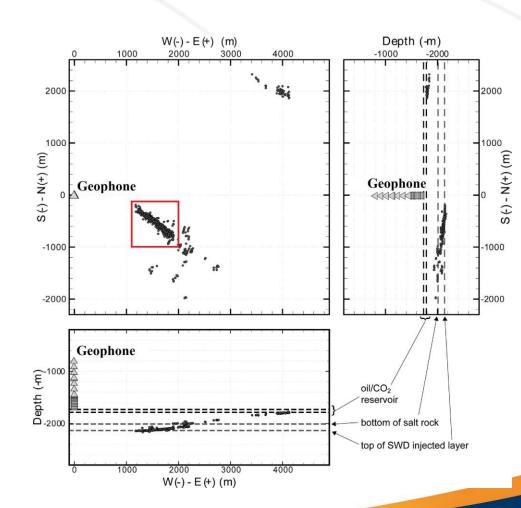




Aneth CO₂-EOR field

- More than 3000 events detected from May 2008 to March 2009.
- 1266 events relocated based on direct, reflection and diffraction waves.
- Events to the south are below the reservoir

(Soma and Rutledge, 2013)

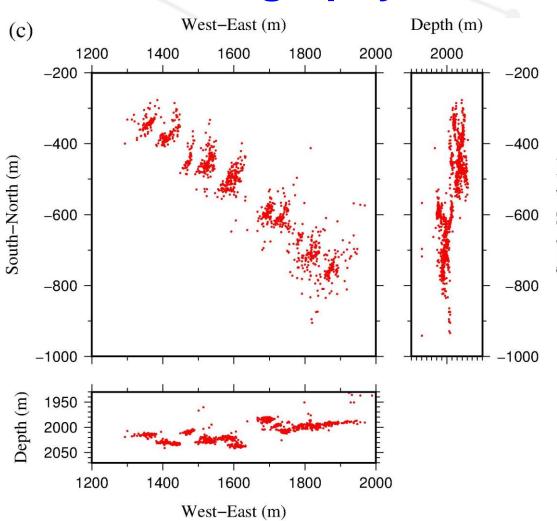




Double-difference tomography

 The events distributing on strips

(Chen et al., CCUS, 2013)



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Questions

- 1. Do microseismic events occur along several fracture zones?
- 2. Are fracture zones newly-generated or preexisting?
- 3. Are microseismic events induced by stress or the waste-water or CO₂ injection?
- 4. What is the geometry of fracture zones?





- 1. Moment-tensor inversion of microseismic events
 - Identifying fracture zones, distinguishing the fluid- or stress-induced events
 - Inversion uncertainty using microseismic data acquired at a single-borehole geophone array
 - Limited azimuthal coverage
 - Poor data quality
 - Adaptive moment-tensor joint inversion method





2. Seismic imaging using microseismic data

- Directly imaging fracture zones
- Imaging sedimentary layers
- Conventional reverse-time migration using explosive or vector source cannot match the radiation pattern
- Reverse-time migration of microseismic data using moment-tensor sources





- 3. Full-waveform inversion of moment tensors and seismic velocity model
 - To improve the seismic velocity model and moment tensor inversion simultaneously





Outline

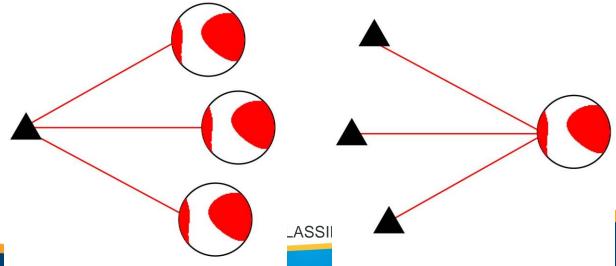
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Adaptive moment-tensor joint inversion method and its application to the Aneth CO₂-EOR field

- Inversion uncertainty with limited azimuthal coverage
- Clustering events with similar seismic waveforms and radiation patterns
- Similar focal mechanisms in the adjacent areas (e.g. Dahm et al., 1999; Rutledge, 2004; Maxwell, 2014).
- Inverting the clustered events with the same focal mechanism







An adaptive joint inversion

- Joint inversion: events in a cluster inverted using the same focal mechanism (strike, dip, rake, ISO and CLVD) but different source durations and moments
- Adaptive inversion: each event further inverted based on the joint inversion result with a search range of ±10° for strike, dip and rake, ±0.05 for ISO and CLVD

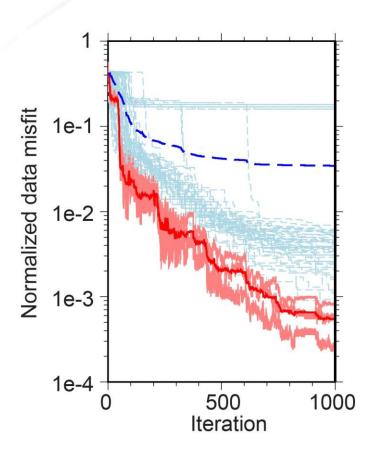


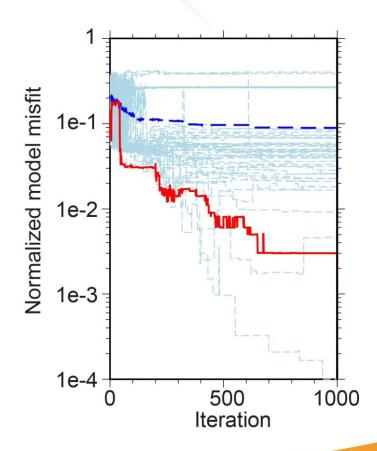


Synthetic test for joint inversion

50 events with the same focal: stk:220 dip:45 rake:0 iso:0.1 clvd:0.2

Same configuration as the Aneth field





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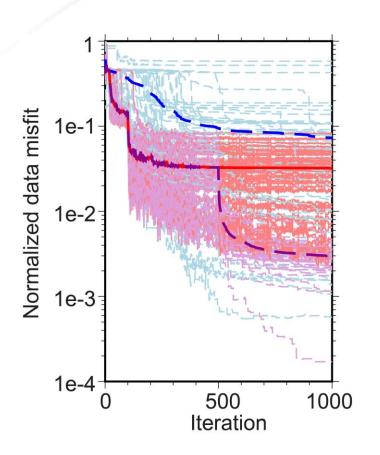


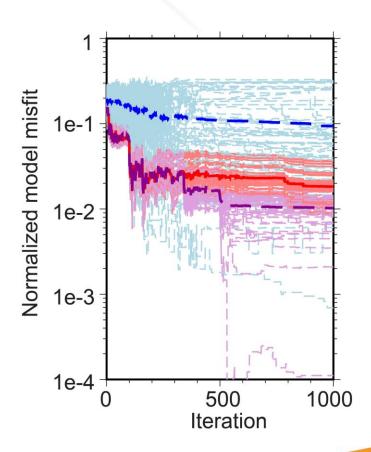


Adaptive joint inversion with varying focal

50 events with varying focals:

stk:220 dip: $45 \pm (up to 10)$ rake:0 iso:0.1 clvd:0.2







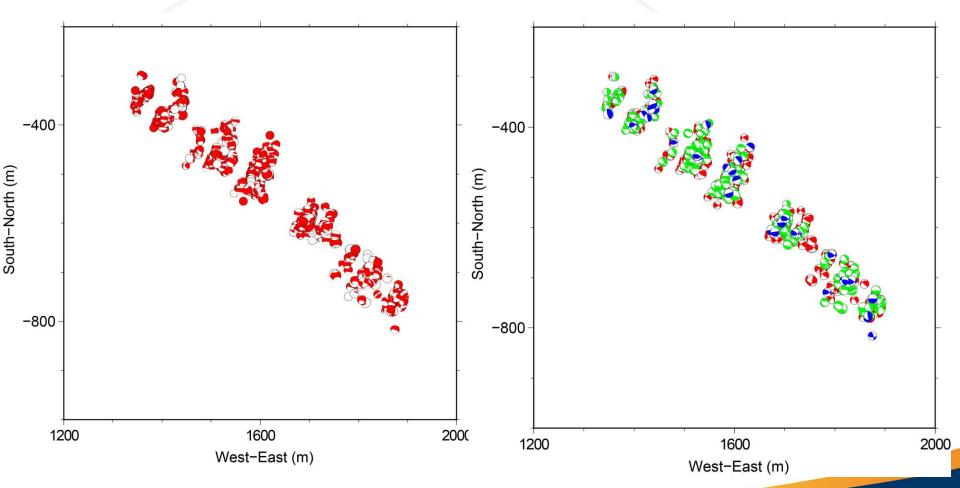




Individual inversion

Left: full moment tensor

Right: double couple only

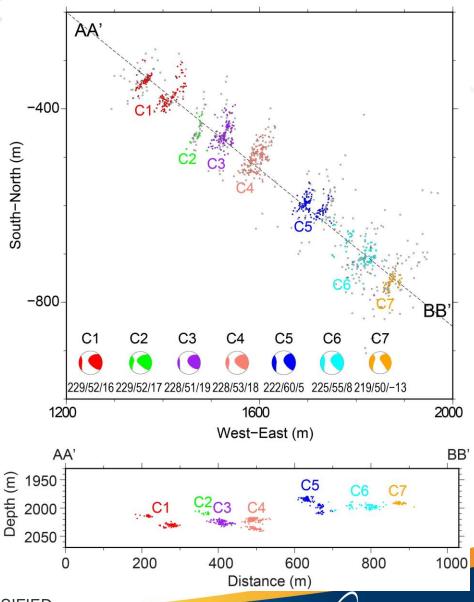


NIS



Joint inversion result

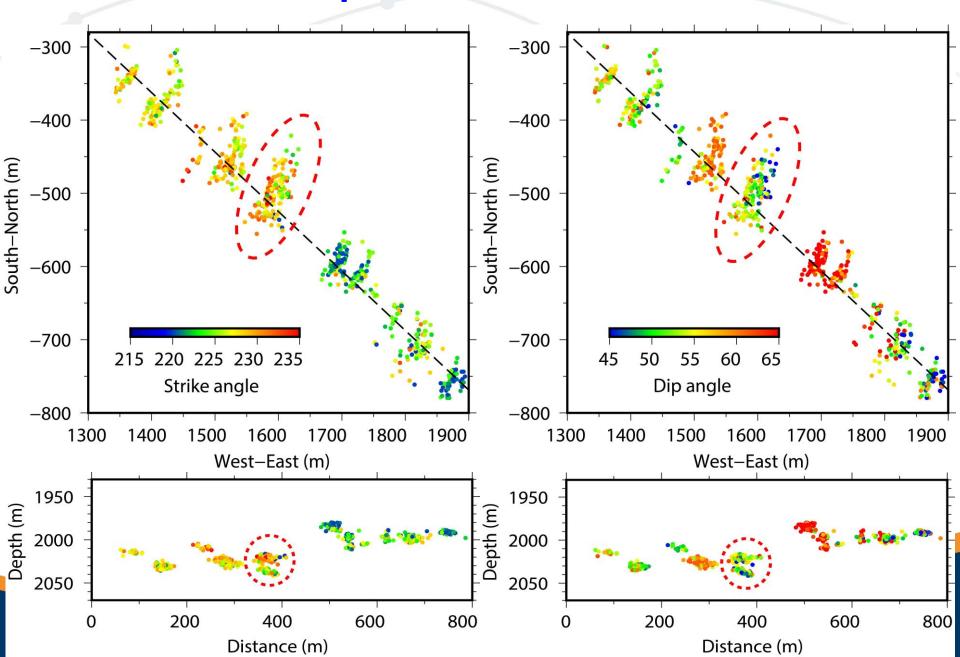
- Seven clusters based on similarities of microseismic waveforms and radiation pattern
- Consistent but slightly varying focal mechanisms of the seven clusters
- Large non-double couple component





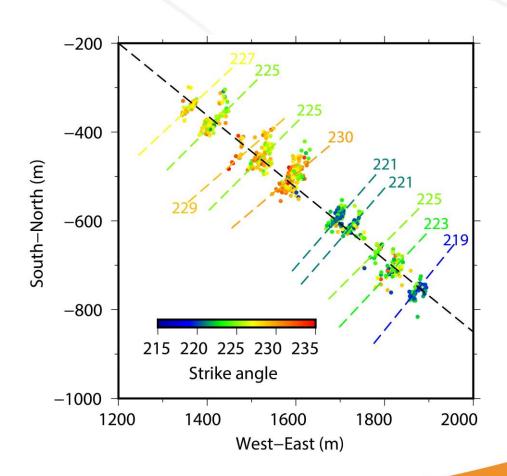


Adaptive inversion result



Strike variations of focal mechanism

- The varying strikes of focal mechanisms consistent with the event distribution
- Strike-slip focal mechanism indicating pre-existing fracture zones.

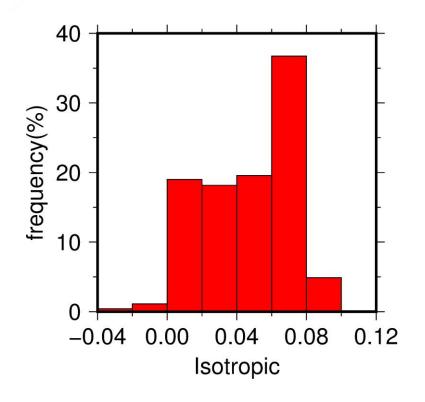


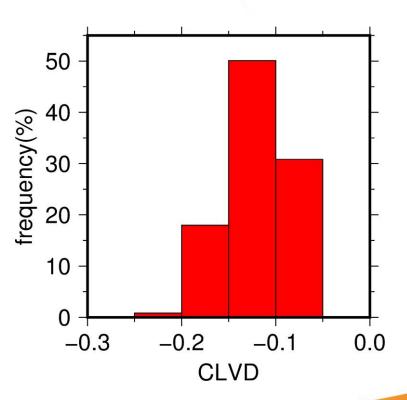




Significant non-double-couple component

- ➤ ISO between 0 and 0.10; CLVD between -0.2 and -0.05.
- Injection-induced seismicity

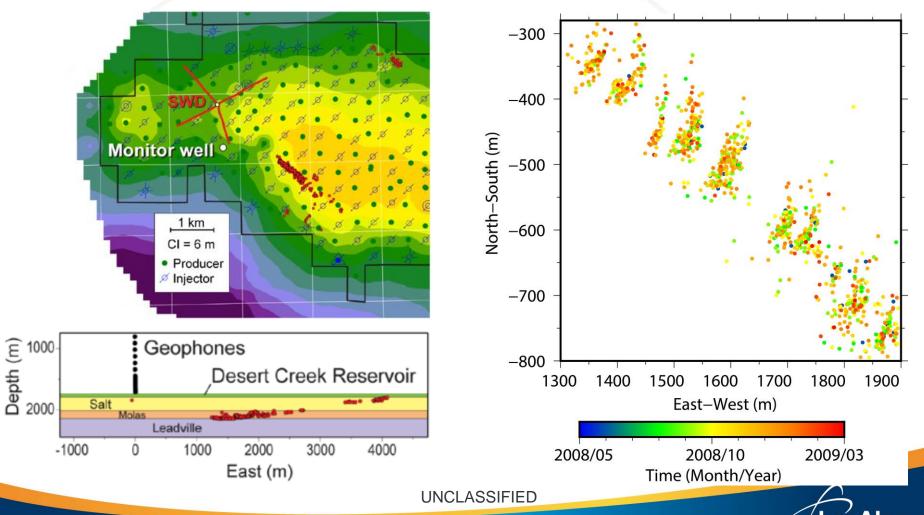






CO₂-injection-induced events at the reservoir basement

Events induced by CO₂ injection instead of wastewater





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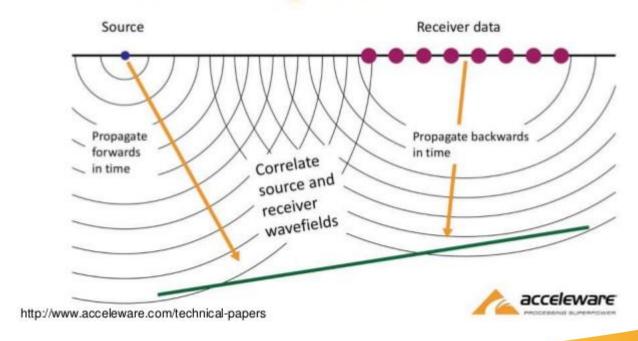




Reverse-time migration of microseismic data using inverted moment tensors

- > Forward propagation of source wavefield in time
- Backward propagation of recorded seismic data
- Imaging condition

Reverse Time Migration



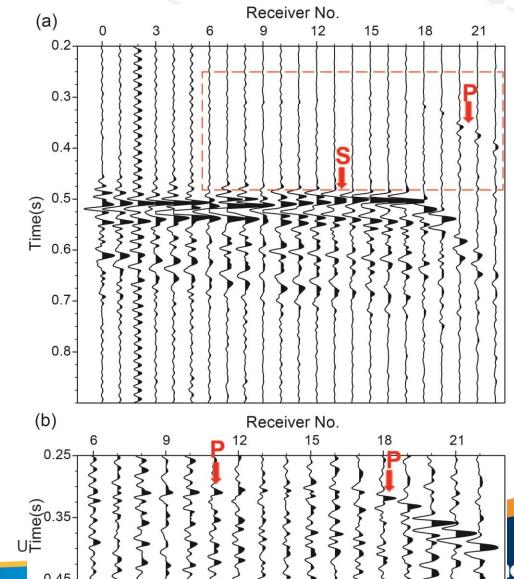






Microseismic event radiation pattern

- Explosive source cannot make use of the strong S waves
- Explosive and vector source cannot match the radiation pattern of the seismic source





OS

Moment-tensor source in finite difference

> Add the moment tensor as the stress in waveform modeling

$$\sigma_{ij} = \sigma_{ij} + \frac{\Delta t M_{ij}(t)}{V}, i = 1, 3, j = 1, 3$$

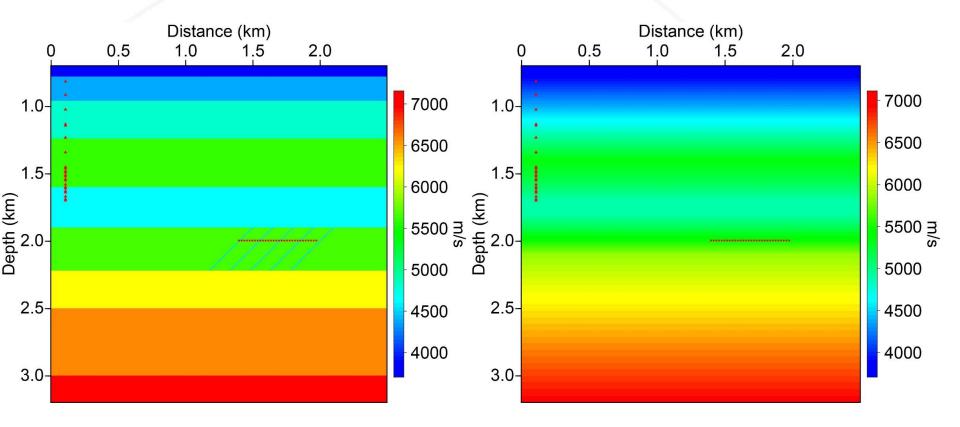




Synthetic test

True model

Smooth model



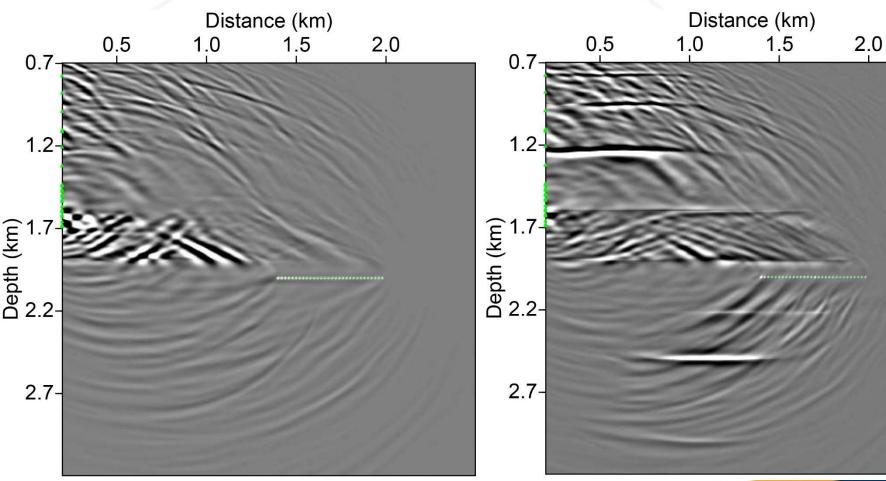




Up and Down going wavefield

Explosive sources

Moment-tensor sources



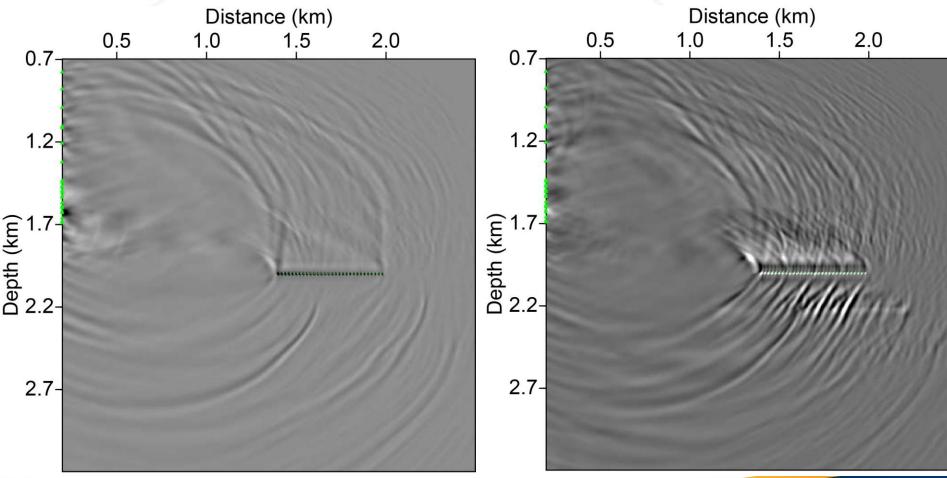




Right going wavefield

Explosive sources

Moment-tensor sources

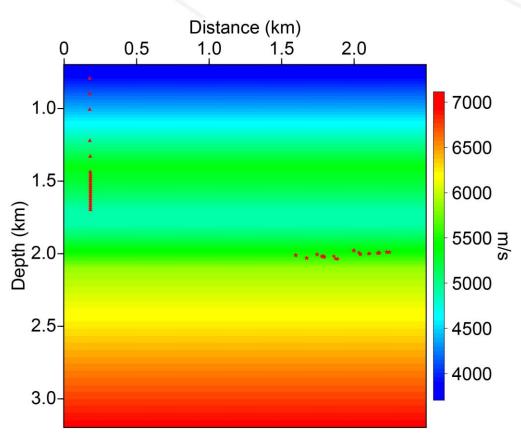






Application to the Aneth field

- Selecting 38 microseismic events from the seven clusters
- Forming a 2D line
- Performing the imaging in a 3D model





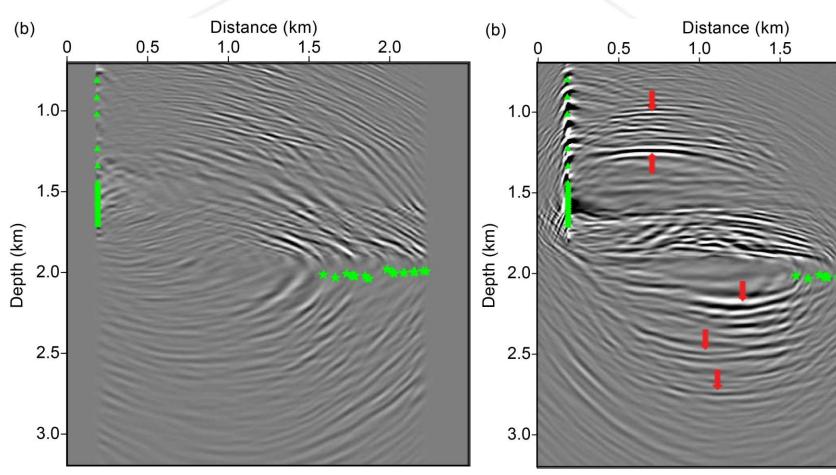


Up and Down going wavefield

Explosive sources

Moment-tensor sources

2.0

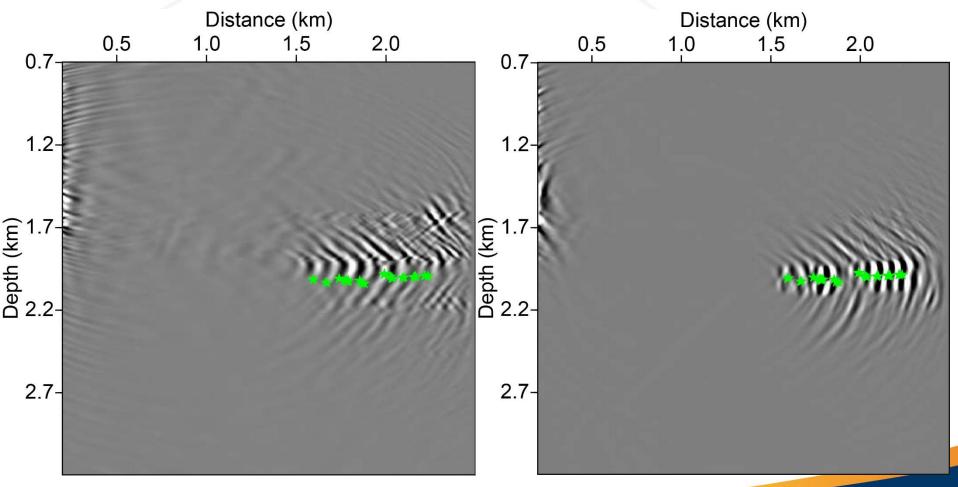




Right going wavefield

Explosive sources

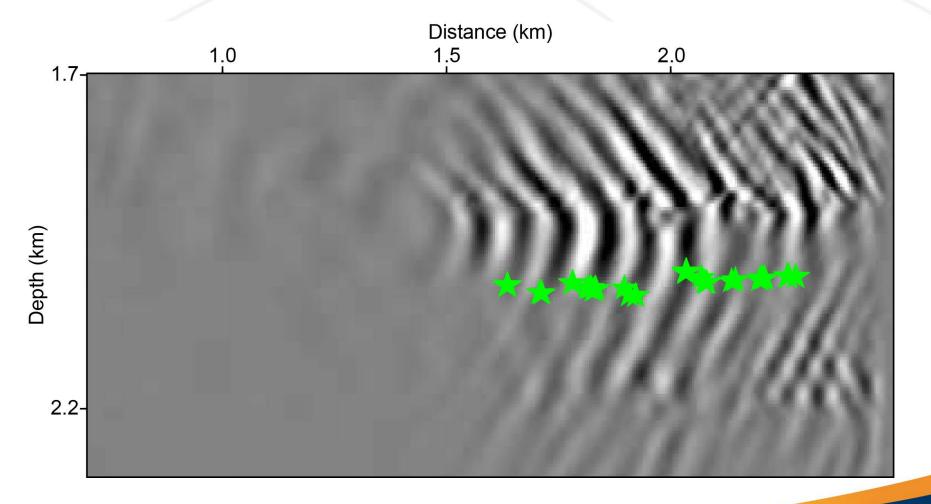
Moment-tensor sources







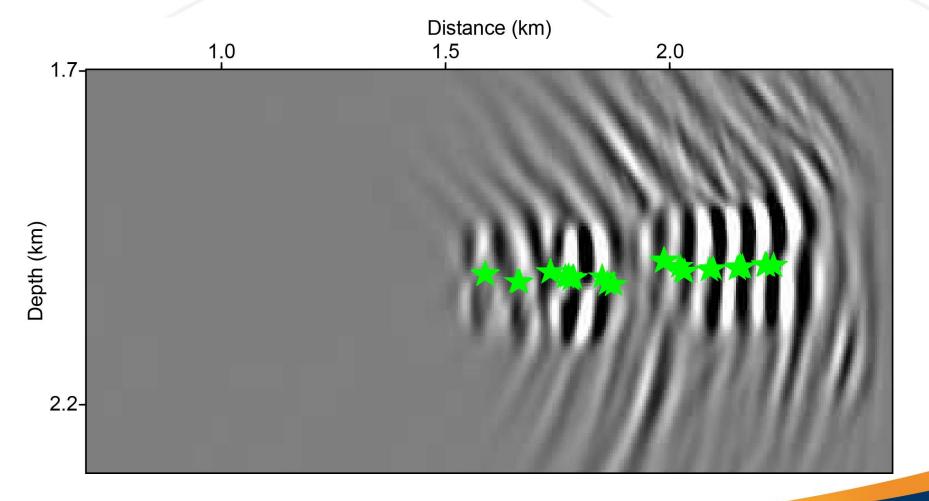
Explosive sources







Moment-tensor sources







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Full-waveform inversion

- Tomography uses arrival times, specially first arrivals
- Full-waveform moment-tensor inversion minimizes the misfit of the whole waveform between data and synthetics
- Providing additional constraints using multiple phases and their amplitudes
- Reducing the inversion non-uniqueness





Full-waveform inversion

- Full-waveform moment-tensor inversion requires an accurate velocity model
- On the other hand, full-waveform inversion of the velocity model needs correct moment tensors
- Develop a full-waveform inversion algorithm to iteratively update moment tensors and the velocity model





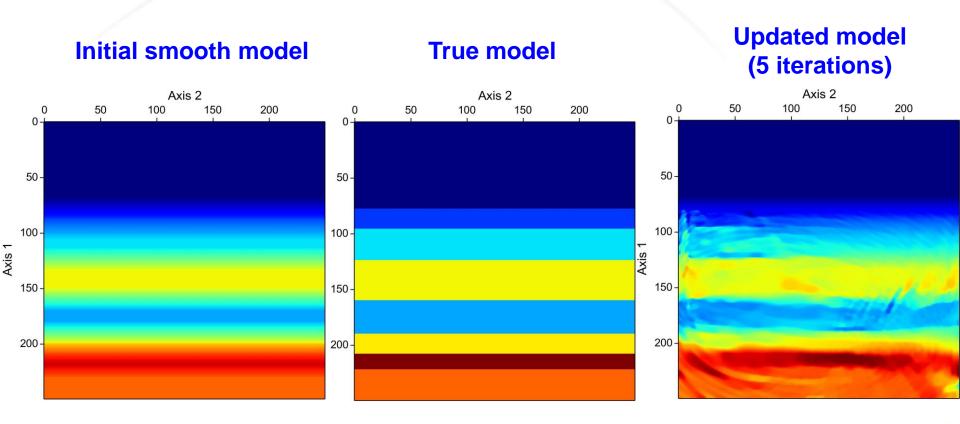
Full-waveform inversion procedure

- Obtaining initial moment tensors through our adaptive joint inversion
- Inverting the velocity model using the initial moment tensor
- Inverting the moment tensor based on the updated model
- Iteratively updating the velocity model and moment tensor until no further improvement





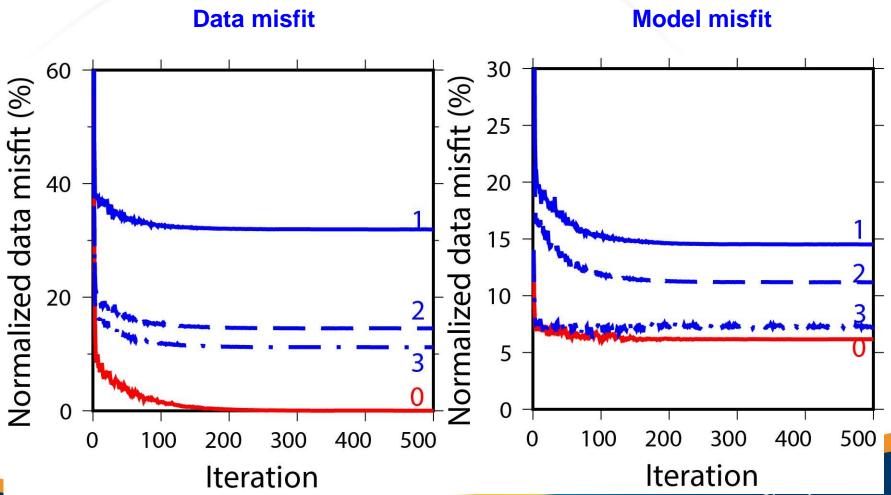
Full-waveform inversion of the velocity model





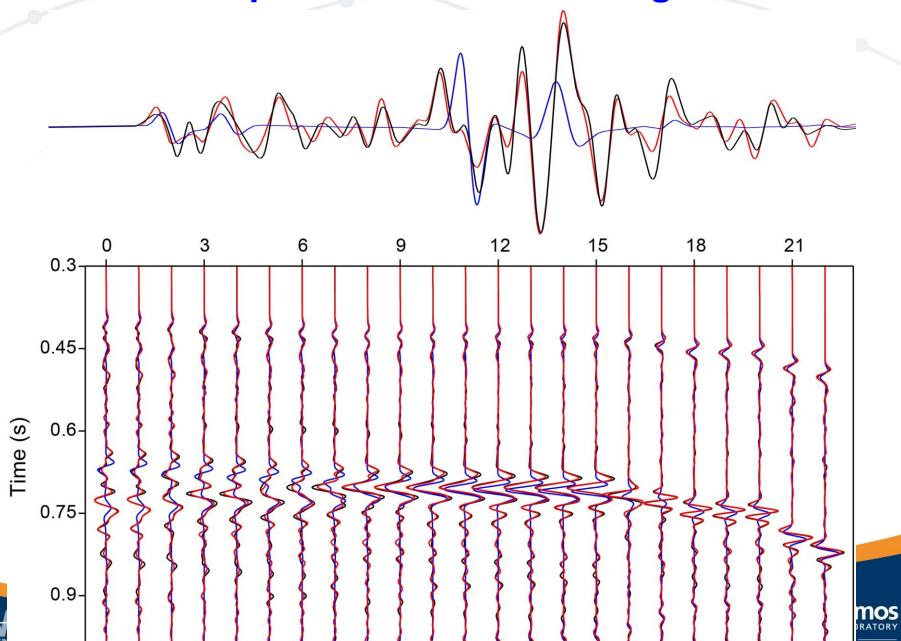


Data and model misfits of moment tensor inversion for different velocity model





Improved waveform fitting





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Conclusions

- 1. Moment-tensor inversion of microseismic data from the Aneth CO₂-EOR field
 - Develop an adaptive moment-tensor joint inversion method
 - Event locations and focal mechanisms: sub-paralleled fracture zones
 - Strike-slip faulting: pre-existing weak zones
 - Large non-double-couple component: pore pressure induced microseismicity
 - Time migration: CO₂-induced
 - Microseismic events induced by the CO₂ injection in the subparallel pre-existing weak zones





Conclusions

2. Seismic imaging using microseismic data

- Develop a reverse-time migration method using inverted moment-tensor sources
- Image several sedimentary layers above and beneath the sources
- Image fracture zones around microseismic event locations
- Produce better images with moment-tensor sources than using explosion sources





Conclusions

3. Full-waveform inversion of microseismic data

- Develop a full-waveform inversion algorithm to simultaneous update moment tensors and the velocity model
- Validate the method using synthetic data





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Thank you for your attention!

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